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THERMAL COATING CHARACTERIZATION USING THERMOELASTICITY

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INTRODUCTION

Synchronous demodulation techniques have been used for some time to measure thermal radiation produced by the small temperature changes associated with elastic stress in materials, the thermoelastic effect[1]. As reviewed in [2], these measurements have been employed primarily for inferring stress distributions in materials from the associated temperature distributions. Images of stress distribution have been made most often by assembling a large number of individual synchronous component measurements using specialized equipment [3]. Other investigators [4,5] have used subtraction of stroboscopic samples to build up similar images. Recently, techniques using full-field synchronous demodulation [6,7] have been reported using equipment [8] which may be configured to perform a large number of thermal measurements. In this paper, the elements of the measurement system are used to provide information useful in characterizing the thermal properties of a coating on a substrate.

COATING CHARACTERIZATION

High emissivity coatings have been employed for many years in thermographic inspections of highly reflective surfaces. As the name suggests, the coating characteristic of interest is the emittance of a particular coating. Thermal protection coatings have also been used and are increasingly used to protect load-carrying structural elements from high temperatures. For these coatings, thermal conductivity is the characteristic of interest. Both emissivity and thermal conductivity are steady-state properties of a coating. For time-varying situations, the response time of a high emissivity coating is also a consideration, as noted in [1]. This response time occurs because the coating has a finite heat capacity and is often a thermal insulator, so its temperature, which produces the detected radiation, lags that of the substrate being measured. The most direct way of lowering the thermal response time of a coating is to reduce its thickness. This stratagem is effective only until the coating is so thin that it is no longer opaque, and so the infrared absorption depth over the spectral range of detector sensitivity becomes another significant characteristic of a high emissivity coat-

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ing. For thermoelastic response, the strains within the coating itself can generate thermoelastic signals, so the coating thermoelastic response when matched in strain to a given substrate becomes another consideration. Mackenzie [9] has formulated the coating response as a thermal wave problem, adding the thermal wave and infrared reflection coefficients to the above set of characteristics of interest. This has resulted in Equation 1 for coating response. In this equation, F represents the infrared flux from the surface, σ is a complex

$$F \propto \frac{A}{e^{\sigma d} - R_a R_s e^{-\sigma d}} \Big(\frac{1}{(\alpha - \sigma)} [1 - e^{d(\sigma - \alpha)}] + \frac{R_a}{(\sigma + \alpha)} [1 - e^{(-d)(\sigma + \alpha)}] +$$

$$\frac{R_m}{e^{2\alpha d}} \Big\{ \frac{-1}{(\sigma + \alpha)} [1 - e^{d(\sigma + \alpha)}] + \frac{R_a}{(\sigma - \alpha)} [1 - e^{d(-\sigma + \alpha)}] \Big\} \Big) +$$

$$\frac{Q}{\alpha} \{ [1 - e^{-\alpha d}] + R_m e^{-2\alpha d} [1 - e^{\alpha d}] \} \tag{1}$$

wavenumber given by $(1+i)(\pi f/k)^{1/2}$, where f is the frequency of oscillation and k is the thermal diffusivity of the coating, A is the amplitude of temperature oscillation from the substrate, which is considered to be only slightly loaded thermally by the coating, Q is the ratio of thermoelastic coefficients between the coating and the substrate at equal strain, d is the thickness of the coating, R_a is the thermal wave reflection coefficient from the coating/air boundary, R_s is the thermal wave reflection coefficient at the coating/substrate boundary, R_m is the infrared reflection coefficient at the coating/substrate boundary and α is the infrared absorption coefficient for the coating.

THEORETICAL COATING RESPONSE

Equation 1 describes a complex response which depends on several intrinsic parameters of the coating as well as coating thickness and the frequency of the oscillating temperature boundary. Figure 1 shows the amplitude and phase portions of this response as a function of frequency and coating thickness. The values for the intrinsic properties are those chosen by Mackenzie for a paint. The qualitative features of this response are similar to many high emissivity coatings. Figure 2 shows the amplitude portion of the response as a contour plot. For thick coatings and low frequencies, a triangular plateau is seen with a

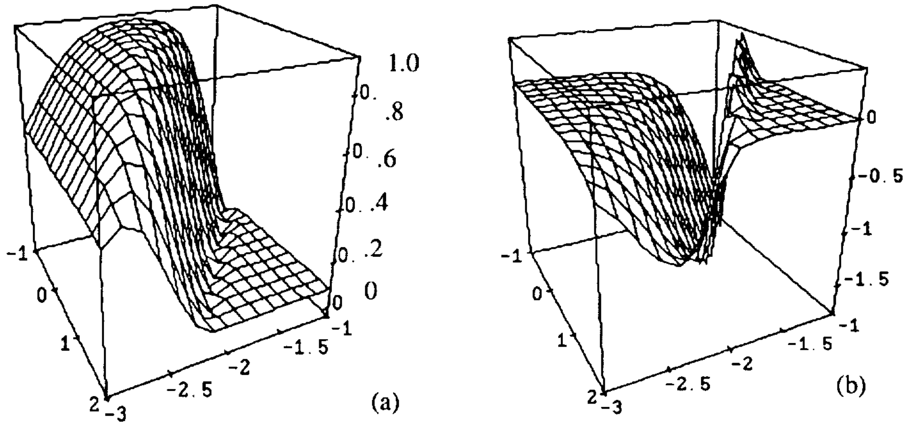

Fig. 1. Theoretical amplitude (a) and phase (b) response of a hypothetical coating to cyclic stress in the substrate. Base axes are log frequency(Hz) on left side and log thickness (cm) along front. Vertical axes are relative response for (a) and phase angle in radians for (b).

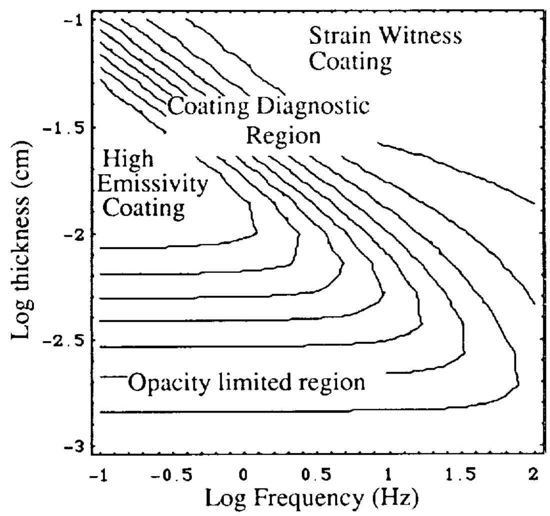

Fig. 2. Contour plot of the amplitude response of a coating as given by Eq. 1 using physical properties appropriate for a typical paint. Regimes in frequency-thickness space of operational and diagnostic significance are indicated for the amplitude response shown.

maximum amplitude and nearly zero phase. It is within this plateau that the coating acts as a high emissivity coating, faithfully representing substrate temperature as emitted radiation. At small thicknesses, the coating becomes increasingly transparent to the infrared radiation of interest, and the response amplitude decreases accordingly. At larger thickness or higher frequencies, the response develops a substantial phase shift as well as a decrease in amplitude. This is because the thermal wave propagating through the coating attains a wavelength on the same order as the coating thickness. On the log-log representation given here, the contour lines form a diagonal pattern of straight lines terminating in the curved high-frequency end of the high emissivity plateau as they encounter the low absorptivity cutoff. The high frequency-high thickness reduction in amplitude does not continue indefinitely, but rather is terminated in a region of flat response at zero phase, merging with a small phase fluctuation indicative of phase interference from multiple effects. This high frequency-large thickness regime is the thermoelastic response to strain in the coating itself, the thermal waves from the substrate being completely absorbed in the coating. Because the synchronous infrared response in this regime is responsive only to the strain of the substrate, it may be termed a strain witness coating.

For a coating of thickness sufficient to act as a high emissivity coating, the frequency response is expected to have one value at low frequencies and transition to another level at high frequencies through a linear fall-off region, the fall-off rate being approximately 1.5dB/octave. If a characterization of the coating is desired, it must be measured through the range of frequencies from the plateau through the complete transition region to the strain witness regime.

Differential formula

Experimental considerations make it desirable for coating characterization to perform a difference measurement between coatings of two different thicknesses. If multiple pass coating techniques are used to produce the thickness variations, the expected situation is one in which the thickness of the coatings are unknown, but the thickness ratios are considered to be the ratios of the number of passes used to coat each of the contrasting thickness areas being measured. Equation 1 has been used to produce numerically plots corresponding to those in Fig. 1 for amplitude ratios and phase differences of observed surface temperature

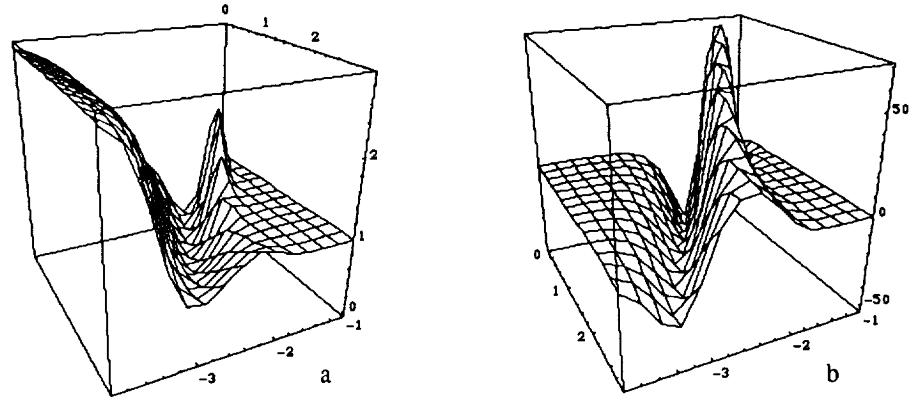

Fig. 3. Amplitude ratios (a)and phase difference (b) for two coating thicknesses in the ratio of 3:1 of observed thermoelastic surface temperature fluctuations as a function of the frequency and thickness of the thinner coating. Coating properties and base axes are the same as for Fig. 1. Phase difference is in degrees.

fluctuations. Figure 3 is an example for a thickness ratio of 3:1. In this example, the opacity limit of the thin layer and the thermal propagation fall-off in the thick layer combine to eliminate the amplitude response of an emissivity enhancing coating.

EXPERIMENTAL TECHNIQUE

The frequency requirement for thermal waves to obtain substantial phase contrast on coatings of thickness relevant to production applications necessitated two extensions of present techniques in the areas of thermal wave production and data interpretation.

Full-Field Synchronous Demodulation

The thermoelastic temperature variations are on the order of a few thousandths of a degree, generally below the detection level of commercially available scanning thermal imagers. Signal averaging is therefore used to reduce the random noise of the imager signal. For full-field synchronous demodulation [7], the experimental arrangement of equipment is shown in Fig. 4 The imager signal, which is available in a standard video format, is directed to sequential frames in a digital image processing system at the video frame rate. The number of frames used is chosen to collect a whole number of complete stress cycles, which are

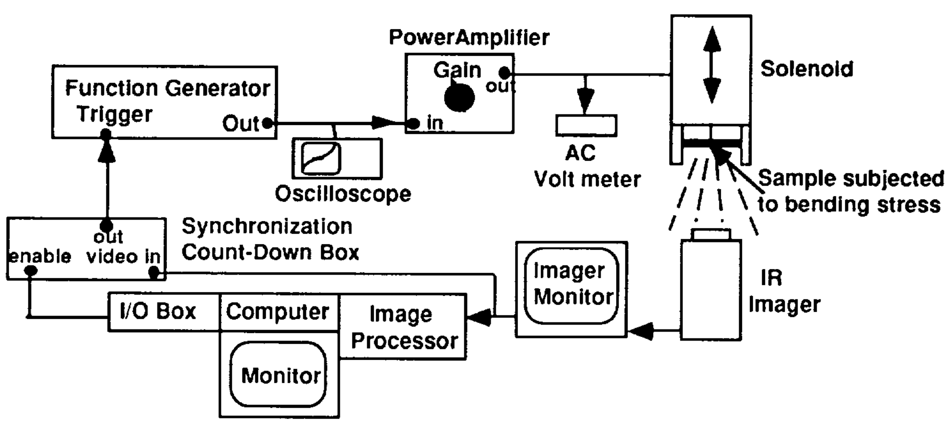

Fig.4. Schematic diagram of experimental equipment.

driven at appropriate frequencies. The cycle is repeated a number of times, summing the data in the image processor frames. Phase synchronization is maintained with a synchronization box in concert with the triggered function generator, so that each summed frame in the resulting data set represents a narrow range of phases. After data acquisition, the data in the image processor are analyzed pixelwise into a mean value, amplitude and phase at the oscillation frequency, producing images of these quantities.

Interpretation of Aliased Data

The video frame rate in our system is 30 Hz, and that is also the sampling rate for our data. Standard signal analysis theory places a limit, the Nyquist frequency at 15 Hz., on the harmonic content of a signal which may be unambiguously described by a series of samples. Signals at frequencies higher than the Nyquist frequency for a given sampling rate are expressed at frequencies below the Nyquist frequency in harmonic analyses, a process known as aliasing. With unknown or broad band signals, the most common way of treating aliasing is to assure that the sampling element in a measurement never experiences signals above the Nyquist frequency. In our case, the objective is to present the digitizing element with a narrow band signal at some frequency beyond the Nyquist frequency, avoiding the Nyquist frequency and its integral multiples, so that the analysis, appearing below the Nyquist frequency, can be related directly to the known frequency of oscillation. If f_r is the real frequency of operation and f_a is the apparent frequency of observation, the two are related by $f_a = |f_r - n/\Delta|$, where n is a whole number needed to bring the value of f_a below the Nyquist frequency and Δ is the sampling interval in seconds. n may be considered the order of the alias. The phase of a point in the aliased image is equal to the phase of the same point in the real image, but because the images are scanned at a constant rate, the real phase difference between two points in an image is the apparent phase difference times the sign of the expression $(f_r - n/\Delta)$ used to calculate the apparent frequency. Using these formulas, the frequency at which an apparent image will be found can be determined, and its phase data from the apparent image can be related to the phases in the real image.

High Frequency Stress Source

There were no servohydraulic machines available to us to achieve the high frequencies needed to analyze coatings. Other stress sources used for high frequencies rely on resonant vibrations, and thus are narrow band or tuned by reconfiguring mass distribution. In order to increase the frequency and maintain the wide bandwidth desired, a new stress source (Figure 5) was constructed. This source subjects a substrate plate to oscillating bending stresses which produce opposite alternating stress patterns on the two faces of the plate. At high enough frequencies, the thermal patterns remain on the surfaces rather than diffusing through the thickness of the substrate. The high frequency limit of the system is the low-

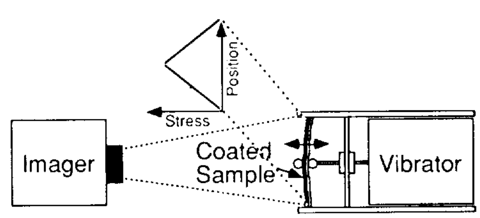

Fig. 5. Schematic diagram showing the thermoelastic source and the imager location. The linear stress pattern is shown on the inset graph, and it oscillates between tension and compression at the vibration frequency.

est plate bending mode of the substrate. This source operated successfully at frequencies up to 160 Hz.

APPLICATION TO COATING CHARACTERIZATION

To assess the applicability to coating characterization, an aluminum substrate was coated with paint, half with a single coat and half with three coats, to produce contrast images appropriate to the contrast formula. Phase and amplitude images were obtained over a range of frequencies, and averaged values were obtained by spatial averaging of the images. The parameters of the differential formula with a 3:1 thickness ratio were adjusted until an approximate fit was obtained. The results are shown in Figure 6 The fitting procedure showed that the positions of the curves were sensitive to the chosen parameters, but the spread of points indicates that the experimental procedure is not yet optimum. It is not unreasonable to expect to achieve consistent amplitude ratios of 5% and phase differences of 5 degrees. The set of parameters required to obtain an optimum fit constitutes the characterization of the coating. In this case, the parameters included coating diffusivity, absorption length for infrared radiation, two reflection coefficients for thermal waves at the two boundaries, coating thermoelastic self-generation coefficient, and the infrared reflection coefficient for the substrate. In summary, the characterization technique shows promise in characterizing coatings which would be applied to metal or heterogeneous surfaces to produce uniform high infrared emissivities.

APPLICATION TO NDE OF COATINGS

The potential for the same measurements to permit nondestructive examination (NDE) of materials was demonstrated by preparing two samples with contrasting squares in an otherwise uniform coating. In one case, the contrast was provided by masking the substrate during one application of paint, so that the paint thicknesses were either five coats or four coats. In the other case, the sample was cleaned, and the contrasting squares were subjected to contamination by grease prior to painting to produce a poor bond. Figure 7a shows the results for the paint thickness squares, while Figure 7b shows results for the weakened

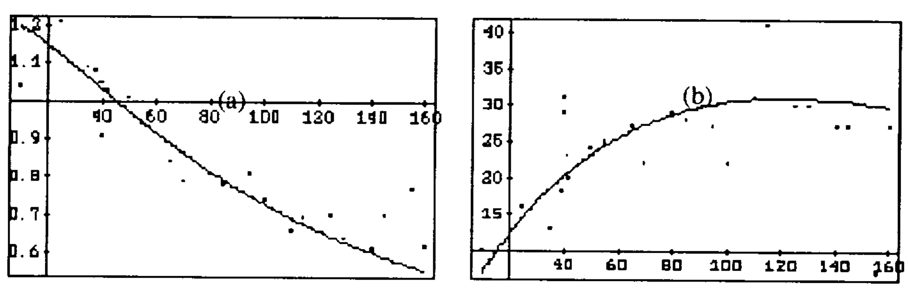

Fig. 6. Amplitude ratio (a) and phase difference(b) data for the paint sample as a function of frequency, plotted on the horizontal axis. Points are experimental data while lines are the fitted curves.

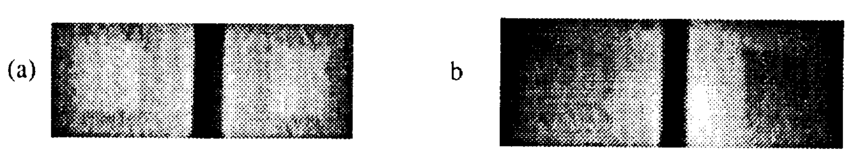

Fig. 7. Thermoelastic amplitude image contrast caused by (a) 5:4 thickness ratio of coatings and (b) grease contamination beneath paint.

bond due to grease contamination. In each case, the black vertical band bisecting the center of the image is the shadow of the central bar used to drive the substrate.

The contrast developed between the two thicknesses of paint and between the contaminated and uncontaminated substrate indicates that using directly driven thermoelasticity as a heat source on coated metal substrates shows promise for inspecting coating materials The inspection has the property that, because the heat used is produced in the substrate rather then propagated through the coating, it constitutes a two-sided inspection with its advantages for speed and spatial resolution. The inspection will be useful in instances for which it is awkward to bring an external heat source to bear on the substrate, but more convenient to produce cyclic stress in the inspected object, and it avoids the problems of reflections and non-uniformity often associated with external heat sources. Its chief difficulty, signal amplitude, can be circumvented in some materials through the application of image processing as was done in the examples shown.

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REFERENCES

1. M.H. Belgen, Infrared Radiometric Stress Instrumentation Application Range Study, (NASA CR-1067), 142 pp.(1967).
2. N, Harwood and W. M. Cummings, eds, *Thermoelastic Stress Analysis*, (Adam Hilger, Bristol, Philadelphia and New York, 1991).
3. D. E. Oliver, D. Razdan and M. T. White, Structural design assessment using thermoelastic stress analysis (TSA), in *State of the Art in Measurement Techniques*, A joint conference of the British Society for Strain Measurement and the Royal Aeronautical Society, 6-9 September 1982.
4. R. H. Blanc and E Giacometti, Infrared Stroboscopy -a method for the study of thermomechanical behavior of materials and structures at high rates of strain, *Int. J. Solids Structures 17*, pp. 531-540,(1981).
5. C. S. Welch, *Quantitative Non-destructive Testing*, Annual Report for Cooperative Agreement NCC1-50 between the College of William and Mary and NASA Langley Research Center, 22pp + Appendix,(1985).
6. L. Chen, T. Ahmed, H. J. Jin, X. Wang, P. K. Kuo, L. D. Favro, R. L. Thomas, A. Demana and J. Thomes, Thermal wave lock-in imaging of cracks in Cu microbridges embedded in polyimide, in *Review of Progress in Quantitative NDE, Vol 11B*, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1992), pp. 1933-1937.
7. C. S. Welch, K. E. Cramer and D. S. Dawicke, Thermographic Inspection of Fatigue Cracks in Riveted Plates, Proceedings of the 1991 SEM Spring Conference on Experimental Mechanics, pp. 239-243,(Soc. Experimental. Mechanics,1991).
8. C. S. Welch, W. P. Winfree, D. M. Heath, K. E. Cramer and P. A. Howell, Material Property Measurements with Post-Processed Thermal Image Data, *Thermosense XII*, pp. 124-133(SPIE Vol 1313,1990).

9. A. K. Mackenzie, Effects of surface coatings on infra-red measurements of thermoelastic responses, *Stress and Vibration: Recent Developments in Industrial Measurement and Analysis*, pp 59-71,(SPIE Vol 1084,1989).